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14. ABSTRACT

The goal of this work was to develop and test new technologies, breaking down the barriers that block more surgeons from attaining and continuing to practice (without injury or pain) high levels of skill in minimally invasive surgery (MIS). This project developed new technology by concentrating on three major research thrusts: Smart Image: the project developed and evaluated new approaches for extracting, fusing, and presenting information cues from imagery and other data sources; Configurable Display: the project developed new approaches for presenting existing data (video, CT data) and extracted cues (3D reconstruction, haptic cues, etc.) to the user within a flexible, configurable display environment; Ergonomic Assessment: the project used existing technology and built new techniques as needed to acquire crucial ergonomic data relative to key factors of patient position, technology configuration, and instrument design.

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Introduction

Information cues available in laparoscopy and other forms of minimally invasive surgery are impoverished relative to cues available in open surgery. Acquiring surgical skill in such an environment is extremely challenging. Even after mastery, continued practice can lead to problems for the surgeon as indicated by frequent incidence of pain and injury associated with laparoscopy. The long-term impact on the surgeon performing these procedures is largely unknown.

The goal of this work has been to develop and test new technologies that could break down the barriers that block more surgeons from attaining and continuing to practice (without injury or pain) high levels of skill in MIS. This project developed new technology by concentrating on three major research thrusts:

- **Smart Image**: the project developed and evaluated new approaches for extracting, fusing, and presenting information cues from imagery and other data sources.
- **Configurable Display**: the project developed new approaches for presenting existing data (video, CT data) and extracted cues (3D reconstruction, haptic cues, etc.) to the user within a flexible, configurable display environment
- **Ergonomic Assessment**: the project used existing technology and built new techniques as needed to acquire crucial ergonomic data relative to key factors of patient position, technology configuration, and instrument design.

Research Accomplishments

Smart Image

Stereo Probe Calibration

A Stereoscopic Endoscope is an endoscope with two optical paths, either separate or shared, creating two images related to one another by a measurable disparity shift. Such an endoscope can be used to generate a stereoscopic view for a surgeon, as with the DaVinci robot in use today. In order to use such an endoscope for metric measurement of structures in the operative field, it is necessary to calibrate the dual optical paths according to a camera model. Once calibrated, it is possible to use stereo reconstruction in order to recover Euclidean metric measurements from the endoscopic images.

This measurement capability is extremely valuable in a number of contexts where it is otherwise difficult to gauge the size and scale of the operative field. For example, Fig. 3 shows an image from a laparoscopic ventral and incisional hernia repair where a small patch of mesh is sewn into the abdominal wall to repair the defect that allowed the herniation to occur. Intraoperatively, the size of the defect must be determined so that a mesh patch of the proper size can be introduced into the surgical site through a trocar. The determination of the dimensions of the defect is currently performed using a tape measure, manipulated using graspers. This step requires the introduction and removal of the tape to perform the measurement. Using a stereoscopic laparoscope and real-time reconstruction of the three-dimensional anatomy allows such measurements to be taken on the imagery using virtual measuring tapes.

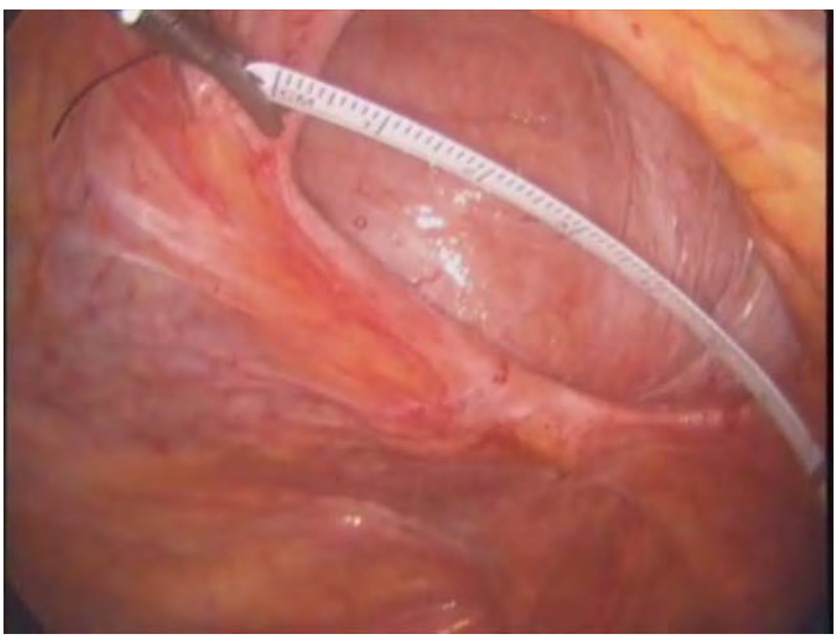


Fig. 3: Laparoscopic view of the measurement tape for hernia repair

In this work we report calibration results for a stereoscopic endoscope that support the ability to make instantaneous measurements in the image from a single stereo pair. Our initial experiments also indicate that a the stereo measurement accuracy can be improved by combining the estimates from stereo pairs with monocular-view structure-from-motion estimates derived from tracked features over a number of frames.

Our work yields metric information to reduce the difficulty in estimating sizes without the need for a reference object in the scene or an external tracking system. The stereoscopic system can provide metric information even when only one image stream from the scope is in fact necessary during the procedure (if there is a situation where stereo display for the surgeon is not a requirement).

The lens system of the stereoscopic endoscope where both views use the same optical path creates a calibration challenge because of the difficulty in modelling the system directly as a pinhole. We have developed a staged calibration process that first removes global non-linear distortion from the image by calculating an optimized global solution to a polynomial radial distortion model. We use three free parameters in the model, including two parameters for the radial decentering and a third radially symmetric coefficient. The first stage uses images of straight lines in order to solve for an optimal set of parameters that minimizes the global distortion according to the model. The constraint is that straight lines in the scene must remain straight in the image under the pinhole perspective projection.

The solution to the distortion model allows the input images to be unwarped according to the parameters of the radial distortion model, which serves as input to the second stage of the calibration. This stage uses known fiducials on targets in order to solve a system of equations for the intrinsic parameters of the camera. Once this optimization has been completed, it is possible to use the two calibrated optical paths for stereo matching (in a single corresponding frame) and 3D reconstruction.

Using a single stereo pair, a matching structure yields a 3D point. We augment this measurement with a set of equations over multiple frames that assume the matching structure can be tracked for some set of frames. By combining 2D and 3D constraints as position estimates from stereo and estimates from 2D feature-based structure-from-motion equations we are able to achieve a tighter bound on the accuracy of the measurement process.

Results from each stage of the calibration process show (1) how distortion is removed from the stereo pair; (2) the intrinsic parameters calculated from the unwarped images of known fiducial patterns; (3) the error in the 3D reconstruction of known points in the scene; and (4) estimates of the relative error for measurements in the operative field at known distances from the scope.

With respect to (1), once the global unwarp is applied to the image the mean error in pixel coordinates is 5 (reduced from as much as 20-30 for many scopes). The intrinsic parameters calculated from these unwarped images yield projection matrices with mean reprojection errors of 3 pixels (for the set of input values). Using these matrices for stereo reconstruction, the mean error in the 3D position of reconstructed points is 8 mm near the center of the image field to 15 mm near the edge. These measurements are relative to depths across the working volume of

approximately 125 mm. The results indicate that bench calibration of stereoscopic endoscopes can be done to a degree that is good enough to make instantaneous measurements for procedures like hernia repairs and estimates of sizes and areas of regions of interest. Errors in measurements from stereoscopic pairs alone lead us to examine the fusion of data over multiple frames using structure-from-motion in order to narrow the error profile and extend the applicability of the feature to micro features. Our preliminary results in the fusion of measurements (using multiple frames and structure-from-motion) indicate we can narrow the accuracy to a mean error of 4 mm across the image field.

Bench calibration of stereoscopic endoscopes can provide a valuable way to make in-the-image instantaneous measurements from a single stereo pair with enough accuracy to save time in certain procedures where metric measurements are necessary for making decisions and recording anomalies. We have a complete bench calibration protocol for our scopes, with improvements in the lens distortion model (four-parameter model – two for radial and two for tangential), which yields re-projection errors of less than 0.25 pixels for camera intrinsic parameters. An example bench calibration result with calculated lens distortion appears in Fig. 1 below.

The stereo scope calibration gives our toolset the ability to perform through-the-lens, on-demand measurement within a working volume of 60 mm to sub-millimeter accuracy. As a result it is possible to measure anatomical features (e.g., defects, structures) within a predictable error model when using the stereo scope during training or surgery. We are working on the user interface issues of incorporating this measurement capability into the standard set of tools during scope use, and in structuring a set of tasks around the use of through-the-scope measurement in order to determine how this tool can affect efficiency. In particular we are interested in the time it takes to complete a hernia repair given that the scope-based measurement can replace the standard practice of viewing a measuring tape to estimate patch repair size.

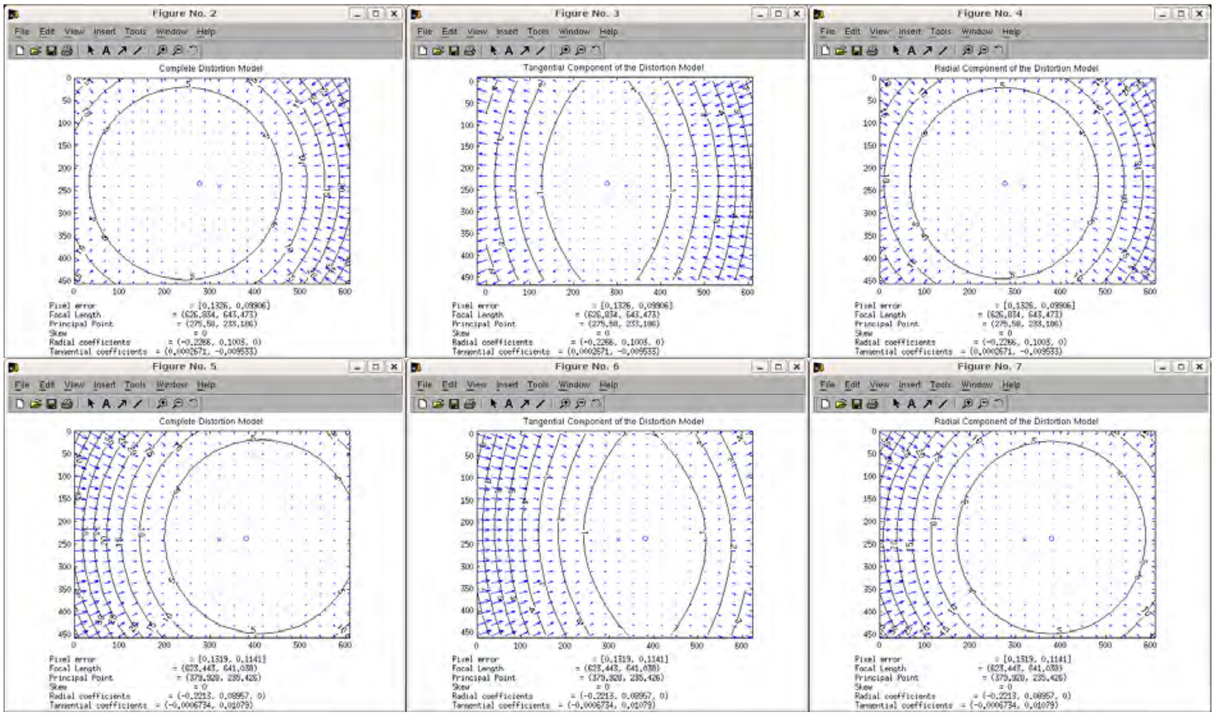


Fig. 1: Composite, tangential, and radial components of the distortion model for the left (top) camera and the right (bottom)

In support of the technology needed to acquire data for the cognitive studies, we implemented the video effects including image rotation, change in scale, and simulation of blood masks and focus distractions. Additionally we performed a number of software and hardware related improvements to make the experimental environment more robust, including the removal of hard-coded data acquisition paths, a cleanup of the CVS (revision control) code base, and the deployment of a set of de-interlacing methods to improve the resolution and performance of the real-time video display environment. These enhancements to the experimental environment run over the general simulation system in real time and can be toggled through a command interface as necessary.

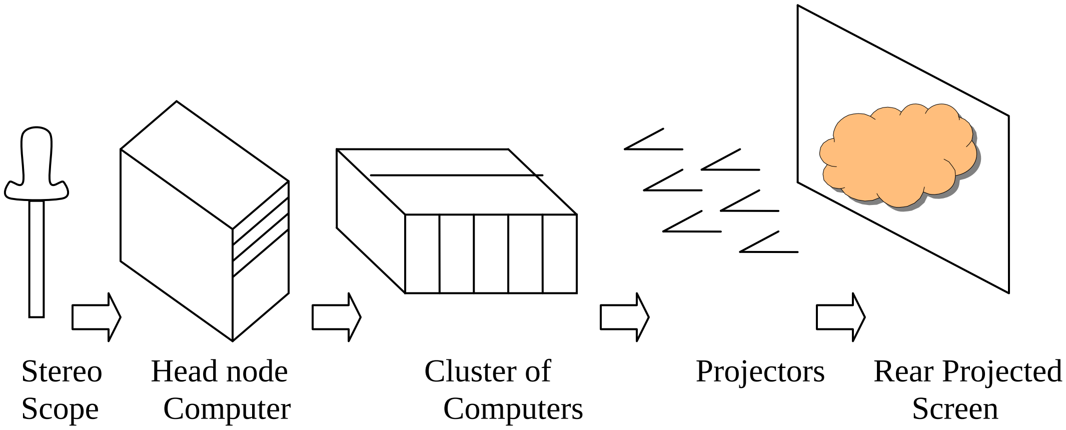
Configurable Display

Large-Scale Projection of Stereo Images from Laparoscopic Probe

Large scale projection of stereo images is a seamless stereo display formed by using two pools of calibrated projectors. The display is used to render high resolution stereo images with depth cues, thus creating a realistic 3D view for the user. The display can be used in multi-viewer environment and also for training purposes.

A large-scale projection system of stereo images is a complex system involving many hardware and software components. The hardware components of the system include two or more projectors, a camera, a gigabit network, a cluster of computers, each of which is connected to a

projector, a projection screen, polarized viewing goggles, polarized filters, and heat resistant custom designed filter mounts. The software components include proprietary stereo calibration software, the Chromium distributed rendering software framework, and the custom built OpenGL stereo applications.



Pipeline of the large scale stereo image projection system

The projectors are divided into two sets, each set representing either a left-eye view or a right-eye view. Each set of projectors is independently calibrated using the functionality of VIBE calibration described above. The calibration information of the two views is processed and the stereo parameters are calculated. The OpenGL stereo applications use these stereo parameters to render the stereo display. The user only has to designate each projector as either left or right. No further user interaction is needed to calibrate and render the stereo display. Synchronization is provided at the image capture end and as well as at the image rendering end of the pipeline.

With eight projectors and eight render nodes, a 4X4 tiled stereo display is formed with a resolution of about 2000 X 1500 pixels. In our current system implementation the frame rate on gigabit network is around 12-14 frames per second. We are in the process of analyzing the performance and sensitivity of the current system with a goal of producing stereo video in the 25-30 frames per second range.

Deployment of the REVEAL Display System at UMMC Simulation Center

A combined motion capture/immersive display system has been deployed in the Simulation Center at the University of Maryland Medical Center. The system was deployed in a decommissioned OR in the South hospital that is being refit for use as a simulation, training and research center. The deployed system consists of custom fixtures, a self-calibrating immersive display similar to that deployed in the UK REVEAL lab, and a Vicon motion capture system. The system supports the ergonomic assessment portion of REVEAL at the University of Maryland.

Custom Fixtures. A custom-built truss system provides a flexible mounting system for locating cameras, projectors and Vicon sensors at optimal positions within the laboratory environment. The environment can be reconfigured rapidly based on the demands of a particular experiment using quick-release clamps.

Self-Calibrating Immersive Display. A self-calibrating immersive display with a curvilinear rear-projection screen for use in monocular and stereoscopic display configurations was deployed. The basic hardware/software environment is similar to that deployed in the University of Kentucky's REVEAL laboratory. Changes have been made where the unique constraints of deployment in a simulated OR have diverged from our general purpose laboratory set-up. In particular, the system uses a smaller wrap-around screen designed to maximize the immersive display experience for the surgical team in their customary positions during a procedure.

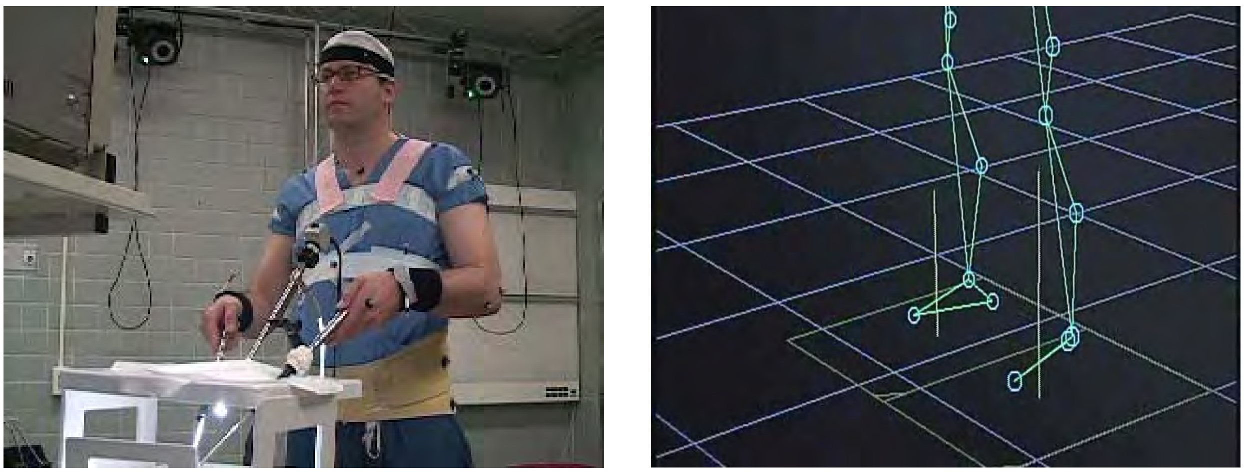


Fig. 1: The subject on the left is being tracked by the Vicon camera system. The system detects joint positions and can estimate angles in a unified 3D coordinate frame.

Equipment and Environment: Vicon motion capture system. A Vicon motion capture system is on-line, providing sub-millimeter precision for the location of objects in three-dimensional space. This system is being used to study instrument and joint positions during laparoscopic procedures to assess the physical requirements of laparoscopy (Fig. 1). This data will be used to produce assessment-oriented data describing the actual demands of current practice, and to design improved surgical gestures that reduce the physical demands of the tasks.

This Vicon system consists of 12 high-speed, high-resolution, infrared, digital cameras. For custom installation of these cameras, a truss system was set up. These cameras have been positioned, aimed, and focused to optimize the size of motion capture volume and the recognition of the 9.5mm markers coated with retro-reflective materials that are placed on experiment participants. Two force plates purchased from AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) have been placed on the floor of the lab. Analog force and moment data are captured, synchronized, and stored through ViconPeak's analog data capture system. Using a mini-DV camcorder, this system also captures images of upper-body movement and stores them with motion capture data. An additional video capture device is used to record endoscopic images used for monitoring instrument movement in the trainer box and evaluating surgical performance. A 16 channel electromyography (EMG) recorder has been purchased to monitor the timing and relative amplitude of muscle activities. This EMG system uses pre-amplifiers integrated into electrodes so signal-to-noise input ratio is enhanced.

Initial Experiments: Pegboard transfer, pattern cutting, endo-loop placement, and suturing/intracorporeal knot tying, four of the five tasks that comprise the Fundamentals of Laparoscopic Surgery (FLS)–the official examination program used by the Society of American Gastrointestinal Endoscopic Surgeons (SAGES)–are being and have been used in our experiments (see example endoscopic images in Fig. 2). Numerous researchers have already validated well that strong correlations between test scores and surgical levels can be obtained through performance analysis of these FLS tasks. Seven, right-handed surgeons with different levels of minimally invasive surgery (MIS) experience were recruited to perform the tasks. During the experiment the surgeons stood with one foot on each force plate. So that surgeons could maintain the correct elbow joint angle while holding surgical instruments at rest, the surgical trainer box was mounted on a height-adjustable platform. A standard CRT monitor that displayed endoscopic images from zero-degree scope was located at eye level in front of the participants. Wearing medical scrub, the surgeons had 39 reflective markers placed on body landmarks so that their body movements could be reconstructed using motion capture technique. Marker placement followed the ViconPeak guidelines for the Plug-In-Gait (PIG) model. Movements of body segments were captured, and joint movements were shown in three rotations - flexion/extension, abduction/adduction, and internal/external. Force plates recorded data of ground reaction forces and moments to provide information for postural stability analysis.

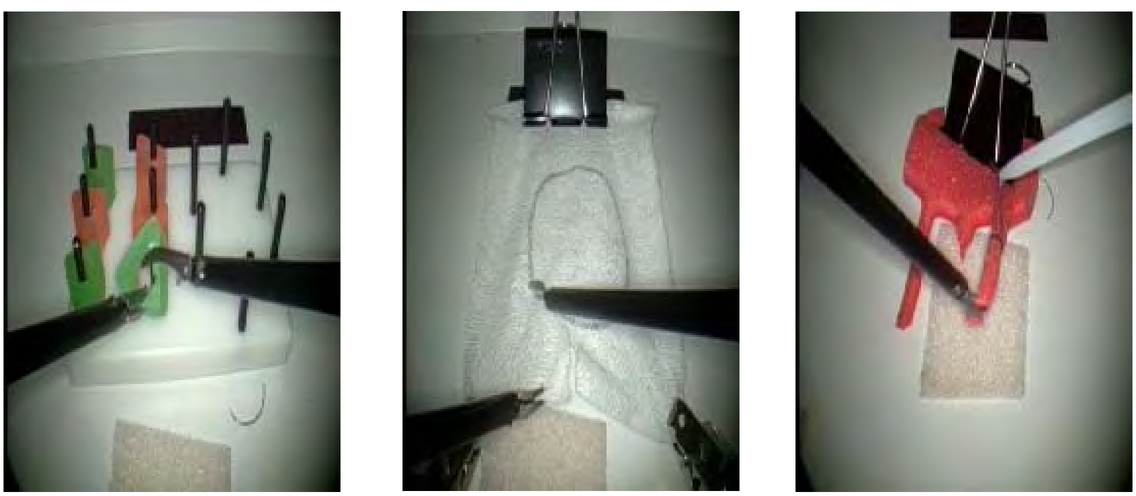


Fig 2: Endoscopic views of baseline tasks

Current Experimental Research Outcomes

Optimizing joint kinematics will most likely allow MIS surgeons to achieve better surgical performance. Joint kinematics characterized by range of motion (ROM), mean joint angle (MJA), and mean joint movement amplitude (MJMA) were correlated to performance time during the FLS pegboard transfer task. MJA varied with different performance skill. Participants requiring the most time to perform showed more mean flexion angles ($r=.684$, $P<.05$) at the left

elbow while maintaining approximately 90 degrees at the right elbow. Regarding the left wrist, more skilled participants, requiring the least time, showed more external rotations ($r=.680$, $p<.05$) while less skilled subjects maintained the neutral position. Less skilled subjects showed more external rotation at the right wrist ($r=-.751$, $p<.05$). ROM and MJMA did not differentiate performance skill levels. This study suggests the development of further investigations on joint movement patterns to formulate joint control strategies for optimal laparoscopic surgery training [4].

It is very important for MIS surgeons to maintain proper postural stability for better surgical performance. Postural stability was correlated to surgical skill level represented by performance time during pegboard transfer, pattern cutting, and endo-loop placement tasks. Center of Pressure (COP) was derived separately from each force plate and then combined to obtain overall COP which showed anterior-posterior (A-P) and medial-lateral (M-L) sway. It was found that each FLS task required unique postural control adjustment. More experienced participants showed smaller COP excursion in A-P direction during pegboard transfer ($r=.912$, $p<.05$) and in M-L direction during pattern cutting ($r=7.888$, $P<.05$). During endo-loop placement, COP excursion was inversely correlated with performance time ($r=-.884$, $P<.05$, $r=-.824$, $P<.05$). This study emphasized that optimized ergonomics should be determined by individual task [5].

When suturing/intracorporeal knot tying, the most difficult of the FLS tasks, was evaluated, joint ROM was used to characterize joint kinematics. During this task, it was found that more skilled surgeons relied less on shoulder movement than less skilled participants. Expert surgeons showed smaller ROM at the dominant wrist and greater ROM at the non-dominant wrist. This research serves as the starting point of more detailed analysis of surgical movement that characterizes the joint movement and joint coordination of expert surgeons [6].

Previous studies in surgical ergonomics have shown that instrument usage, task difficulty, and subject skill level can be correlated to postural stability. However, these studies did not consider the possibility that surgeons may strategically change their stance or joint movement to achieve better surgical outcomes while potentially subjecting themselves to greater kinematic risk. In our study, one highly experienced and skilled surgeon reported the development of carpal tunnel syndrome in both of his wrists. Still, this participant was able to finish both the pegboard transfer and pattern-cutting tasks significantly faster than others, within a minute for each task. To minimize wrist flexion during the pegboard transfer task, the surgeon increased the abduction angle of his shoulder so that his hand and forearm aligned. During pattern cutting, the subject maintained his lower body position and stance while twisting his torso in a strategy that appeared to stabilize a tangential direction in relation to the cutting while maintaining a fixed orientation of forearm, wrist, and hand. In a different trial when circle-cutting was the task, the subject changed his stance primarily by shifting foot position as needed in order to obtain better approach angles for the scissors. These compensatory and strategic movements caused increase in his overall postural sway, yet they did not necessarily represent postural instability. This case study demonstrated that poor postural stability or joint kinematics do not necessarily correlate to poor performance but may instead be positive compensatory or strategic movements. Therefore, background information about participants, which might, for instance, include joint impairment, should be considered as important ergonomic elements, the correlations of which may lead to

more accurate and specific conclusions about optimal postural stability and joint kinematics for minimally invasive surgeons [7].

Custom Development within Experimental Setup: Markers must be placed so that the best camera recognition and body segment definition are obtained. For our experiments, the ViconPeak marker placement guidelines were followed. The ViconPeak Plug-In-Gait marker set was originally designed for analysis of lower and upper body motion in conventional situations. Expecting that more obstacles would be located between markers and cameras in a surgical environment, we have developed custom marker placement that is achieved by using clustered markers. For better data capturing, three or four markers are grouped together and attached to a body segment toward which the cameras are pointed. To define a segment, there should be three markers in each segment. When one marker of a segment is lost during data collection, the segment cannot be defined and biomechanical model stops working. Therefore, one or more extra markers in each segment can be used to missing marker problem and this also supports the need of custom marker. The Plug-In-Gait biomechanical model that calculates kinematic data including joint angles cannot be used as is with a custom marker set. The International Society of Biomechanics (ISB) just recently published an article suggesting new marker sets, segment definitions, and angle calculations [8]. Plug-In-Gait has been shown to cause a well-known surgical movement problem called 'gimbal-lock', which is a unique angle of the shoulder joint. Therefore, a biomechanical model that incorporates new ISB recommendations and custom marker sets is now being developed here as a part of REVEAL project.

Ergonomics

Physical Ergonomics

During this period of performance of the REVEAL project, the University of Maryland portion addressed several ergonomic aspects of laparoscopy. Research was conducted in a dedicated space within the Maryland Advanced Simulation Training, Research and Innovation (MASTRI) Center. This setting contains state-of-the-art biomechanical data collection systems, instrumentation, and commercial and custom-developed software for the measurement of surgeons' postural and upper body movement characteristics during laparoscopic tasks. Additionally, the setting provided the investigator with access to both clinical expertise and a variety of equipment pertaining to surgical simulation training.

The following studies comprise the investigative effort in support of the REVEAL project:

- **Study 1: Correlation between postural instability and compensatory/strategic movements [1-1, 2-1, 2-5]**

  Previous studies in surgical ergonomics have shown that instrument usage, task difficulty, and subject skill level can be correlated to postural stability.[1-3] However; these studies did not consider the possibility that surgeons may strategically change their stance or joint movement to achieve better surgical outcomes while potentially subjecting themselves to greater kinematic risk. In our study, one highly experienced and skilled surgeon reported the development of carpal tunnel syndrome in both of his wrists. Still, this participant was able to finish both the pegboard transfer and pattern-cutting tasks significantly faster than others, within a minute for each task. To minimize wrist flexion during the pegboard

transfer task, the surgeon increased the abduction angle of his shoulder so that his hand and forearm aligned. During pattern cutting, the subject maintained his lower body position and stance while twisting his torso in a strategy that appeared to stabilize a tangential direction in relation to the cutting while maintaining a fixed orientation of forearm, wrist, and hand. In a different trial when circle-cutting was the task, the subject changed his stance primarily by shifting foot position as needed in order to obtain better approach angles for the scissors. These compensatory and strategic movements caused increase in his overall postural sway, yet they did not necessarily represent postural instability. This case study demonstrated that poor postural stability or joint kinematics do not necessarily correlate to poor performance but may instead be positive compensatory or strategic movements. Therefore, background information about participants, which might, for instance, include joint impairment, should be considered as **an** important ergonomic element, the correlations of which may lead to more accurate and specific conclusions about optimal postural stability and joint kinematics for minimally invasive surgeons.

- **Study 2: Postural sway analysis during laparoscopic tasks [2-2, 2-4, 2-5]**
  It is very important for MIS surgeons to maintain proper postural stability for better surgical performance.[4,5] Postural stability was correlated to surgical skill level represented by performance time during pegboard transfer, pattern cutting, and endo-loop placement tasks. Center of Pressure (COP) was derived separately from each force plate and then combined to obtain overall COP which showed anterior-posterior (A-P) and medial-lateral (M-L) sway. It was found that each FLS task required unique postural control adjustment. More experienced participants showed smaller COP excursion in A-P direction during pegboard transfer ($r=.912$, $p<.05$) and in M-L direction during pattern cutting ($r=7.888$, $P<.05$). During endo-loop placement, COP excursion was inversely correlated with performance time ($r=-.884$, $P<.05$, $r=-.824$, $P<.05$). This study emphasized that optimized ergonomics should be determined by individual task.

- **Study 3: Joint kinematic analsysis during laparoscopic peg-transfer** task **[2-3, 2-4, 2-5]**
  Optimizing joint kinematics will most likely allow MIS surgeons to achieve better surgical performance. Joint kinematics characterized by range of motion (ROM), mean joint angle (MJA), and mean joint movement amplitude (MJMA) were correlated to performance time during the FLS pegboard transfer task. MJA varied with different performance skill. Participants requiring the most time to perform showed more mean flexion angles ($r=.684$, $P<.05$) at the left elbow while maintaining approximately 90 degrees at the right elbow. Regarding the left wrist, more skilled participants, requiring the least time, showed more external rotations ($r=.680$, $p<.05$) while less skilled subjects maintained the neutral position. Less skilled subjects showed more external rotation at the right wrist ($r=-.751$, $p<.05$). ROM and MJMA did not differentiate performance skill levels. This study suggested further investigations on joint movement patterns to formulate joint control strategies for optimal laparoscopic surgery training.

- **Study 4: Postural stability analysis during fundamental laparoscopic tasks [1-2, 2-6, 2-9]**
  The physical difficulties experienced by surgeons performing MIS procedures are being given extensive attention by ergonomic researchers.[6-8] We take postural stability, which has

been insufficiently addressed, as one of our prime focuses. The few studies already existing in this area have used the Center of Pressure (COP) excursion range alone. Using COP, we previously correlated postural stability to instrument type and task difficulty in addition to subject skill level. This study extended the investigative scope, particularly in terms of skill level, by broadening analysis to include Center of Mass (COM) and what we uniquely term Postural Stability Demand (PSD). Six subjects with different levels of surgical experience were recruited to complete 3 FLS tasks – circle-cutting, endo-loop placement, and pegboard transfer. Participants performed each task while standing on two force plates while a motion capture system recorded body movements. COP—at the bottom of the feet—is the point where ground reaction force is located. COM is the point at which the mass of the body is concentrated. Principal Component Analysis was used to create an ellipse covering 95% of COP and COM excursions for the calculation of COP and COM sway area. PSD we characterize as the mean distance between COP and COM locations in anterior-posterior (A-P) or medial-lateral (M-L) directions. Correlations between these postural parameters and performance time were analyzed. During circle-cutting, less skilled participants required longer times to complete the task and showed larger sway areas both in COM and COP ($r=.858$, $p<.05$; $r=.779$, $p=.06$). During endo-loop placement, sway areas of COM and COP were smaller for less skilled participants ($r=-.899$, $p<.05$; $r=-.890$, $p<.05$). These results indicated postural control differences between more and less experienced lap surgeons. No significant sway area correlation was found during pegboard transfer. Importantly, during all three tasks PSD in the A-P direction was strongly correlated with performance time ($r=.744$, $p<.05$; $r=.913$, $p<.05$; $r=.772$, $p<.05$). This indicated that less skilled participants experienced increased postural demand equated with higher postural instability. This study demonstrated that variance in postural adjustments could be correlated to skill level and individual task. Strong correlation between PSD and performance time showed potential as an indirect predictive measure of surgical skill levels. Combining COM, COP, and PSD postural data resulted in a more robust analytical tool for identifying postural adjustments with skill level.

- **Study 5: Determination of optimal operating table height [2-7, 2-9]**

  Surgeons seldom change the set height of an operating table once beginning a case and never do so to accommodate difference in instrument handles. Previous studies sought to determine optimal table height without taking into account the influence of different instrument handles.[9] We gave surgeons different styles of instrument handles and free range to choose optimal table height, based on comfort. Board-eligible, Board-certified general surgeons were recruited to complete two FLS tasks: peg board transfer (task 1) as well as intracorporeal suturing and knot tying (task 2). All tasks were conducted on a training stand with adjustable operating table and monitor height (Stryker). Subjects for task 1 were given two disposable pistol grip (PG) dissectors (USSC) and two inline (IL) needle drivers (Ethicon) for task 2. Nineteen reflective markers were placed on each subject's upper body, and 4 markers were placed on each instrument. A motion capture system (Vicon) used these markers to calculate upper-body joint angles and instrument shaft angles. For both PG and IL instruments, the table height was adjusted until maximum comfort was achieved. Kinematic measurements were made while instrument tips were in the center of the operative field. When using PG instruments, optimal table height averaged 98.1cm. When using IL instruments, a significant change was found as the table height lowered by 6.4cm to average of 91.7cm ($p<0.005$). Multiple changes in joint kinematics were observed when

surgeons changed to IL instruments. Notable changes were in shoulder and wrist joint excursions while there was no significant change in elbow angle. With the IL instruments, elevation angle decreased from 45 to 33 degrees ($p<0.005$). Optimal table height differs when surgeons work with PG versus IL instruments. A table height change based on instrument change faces limitations, such as drape and stand rearrangement and time consumption. Given such difficulties, ergonomic factors warranted further analysis to determine if a standard optimal table height for different instrument handles exists or if an ergonomic redesign of handles is warranted. Additionally, our data suggested that wrist position in addition to elbow position significantly impacts surgeon comfort and optimal table height. Further investigation including imaging, display, surgical ergonomics using whole body analysis, and human factors will be conducted as part of our comprehensive research.

- **Study 6: Subtask joint kinematic analysis during laparoscopic peg-board transfer task [2-8, 2-9]**

  Joint angle analysis using variables calculated from task beginning to end is the primary means in surgical ergonomics for understanding joint control.[10,11] These traditional variables, e.g. range of motion, provide general joint movement information; however, they could not differentiate specific patterns required to achieve certain goals of laparoscopic tasks. We proposed a novel method of data analysis that extends our previous findings about characteristic joint kinematics determined from mean joint angle. Here we divided a laparoscopic task into functional subtasks and analyzed joint movement within the subtask's time frame to extract characteristic movement patterns associated with particular surgical maneuvers. Nine right-handed, experienced laparoscopic surgeons were recruited to perform the standard FLS pegboard transfer task. A motion analysis system captured participants' upper body movements while simultaneously recording endoscopic images that allowed task performance to be partitioned. For each subject, left- and right-side data were captured in three rotations—flexion/extension, abduction/adduction, and internal/external—at three joints—shoulder, elbow, and wrist. The transfer of a single disk was divided into four subtasks: pickup, medial transfer (side to middle), lateral transfer (middle to side before dropping), and the actual drop. Joint angles were analyzed within the time windows of each subtask. Data from a representing subject suggested a possible rubric. Each subtask was composed of a unique set of joint kinematics (Table 1). These joint controls were relatively consistent through six repetitions. While left-right comparison in three subtasks showed no significant control strategy difference, during the pickup subtask left side movement involved fewer joints, well known as joint freeze on the non-dominant side. Our study showed that detailed characteristic movement patterns, not fully depictive with traditional analysis, could be extracted when a laparoscopic task is partitioned into functional subtasks. This new approach will enable our investigation of intra- and inter-subject variability of joint kinematics as part of the development of standard joint control strategy matrices for optimal surgical performance.

Table 1. Significant joint movements observed in each subtask

Significant joint movements observed in each subtask				
Subtask	**Sides**	**Shoulder**	**Elbow**	**Wrist**
Pickup	Left	extended	—	extended & radial deviation

	Right	extended	extended	extended, radial deviation & supinated
Medial transfer	Both	flexed, abducted & externally rotated	extended	flexed, radial deviation & supinated
Lateral transfer	Both	extended & adducted	flexed	extended & ulnar deviation
Drop	Both	flexed	—	flexed & ulnar deviation

- **Study 7: Comprehensive literature review of methodological infrastructure in surgical ergonomics [1-3]**

  The rapid acceptance of laparoscopic surgery as a clinical alternative to traditional open surgery sometimes obscures the fact that MIS is still relatively new. Newer still is our realization of the physical demands MIS procedures can make on its practitioners, but those are precisely the issues that the very recent discipline of surgical ergonomics seeks to understand and address. Like all disciplines that start out at once self-contained yet also multidisciplinary, the field of MIS ergonomic research is fast becoming broadened through a variety of different approaches, so numerous that those outside the field as well as many inside the field may possess scant knowledge regarding the vast methodological array of tasks, models, and assessments in use. Publications were located through PubMed and other database and library searches. This study has intensively reviewed what we identified as the primary research components—that is tasks, models, and measurement systems—which form the essential methodology of MIS ergonomics as this discipline moves through its initial maturation stages. In doing so, we have addressed elements including but not limited to background, technologies, applications, drawbacks, and advantages. In closing we discussed limitations and possibilities we saw inherent in these primary research components and proffered suggestions that if put into practice we believe will only augment the credible and useful findings already comprising surgical ergonomic research.

- **Study 8: Assessment of ergonomic risk of assisting in laparoscopy [1-4, 2-10]**

  Ergonomic knowledge related to primary MIS surgeons has been well described.[12-17] Similar studies making the camera assistant subject have not been undertaken. By simulating the assistant's role as a camera holder and retractor during a Nissen fundoplication, this study investigated how camera target locations and grip strategies in addition to fatigue affected the assistant's posture. Seven subjects were studied while performing a camera navigating task. A training box on an OR table simulated an adult patient in low lithotomy position. Each subject was asked to stand on two force plates at the left side of the simulated patient. A laparoscope was introduced into the training box in which four 2 cm circles as targets had been placed on the rear panel in the following locations to the assistant: (1) distal superior, (2) proximal superior, (3) distal inferior, (4) proximal inferior (TARGET). Subjects were instructed to hold the camera with their left hand and point it at a target with their task to match the target to a circle overlaid on the monitor. Simultaneously, a grasper in the right hand was used to grasp and pull one of two rubber bands on the panel. A minute signal moved the subject on to the next target. Each trial had 3 repetitions (PHASE) consisting of 4 targets. Subjects were asked to perform two separate trials, in which the camera was held from the top and then the bottom (GRIP). A 4x3x2 (TARGETxPHASExGRIP) repeated measures design was used for statistical analysis. Weight loading ratio (WLR) was

calculated from the vertical ground reaction forces (VGRF) from left force plate and total VGRF from both plates. WLR=(left VGRF)/(left VGRF+right VGRF)*100. WLR significantly increased ($p<0.005$) with proximal targets (2:80% & 4:79%) compared to distal targets (1:67.5% & 3:67.6%), a result of the distal position of the camera head (TARGET effect). Also shown was a reduced WLR (75%, 74% & 71% respectively) attributed to compensatory strategy to overcome increased fatigue in the left leg over time (PHASE effect, $p<0.05$). The two grip strategies did not show any difference (GRIP effect, $p>0.5$). This study demonstrated that the assistant's left leg disproportionately bore 70-80% of body weight over time, thus creating a high risk ergonomic situation. Ergonomic solutions like camera handle attachments or instructions to rebalance weight should be considered to minimize fatigue and maximize postural stability. Body movement, EMG, center of pressure, and postural stability demand will provide detailed postural and fatigue parameters.

- **Study 9: Surgical ergonomics survey study [2-11]**

  The widely held belief that laparoscopy causes greater strain on surgeons' bodies than open surgery is not well-documented in scope or magnitude. In the largest North American survey to date, we investigated the association of demographic factors with physical symptoms reported by laparoscopic surgeons. 317 surgeons identified as involved in laparoscopic practices completed the online survey. This comprehensive, 23 question survey addressed four categories: demographics, physical symptoms, ergonomics, and environment/equipment. Data were analyzed using chi-square and logistic-regression. 272 laparoscopic surgeons (86.9%) reported physical symptoms or discomfort. The strongest predictor of symptoms was high-case volume, with the surprising exceptions of eye and back symptoms, consistently reported even with low-case volumes. High rates of neck, hand, and lower-extremity symptoms correlated with fellowship training, which is strongly associated with high-case volume. Right-hand symptoms were reported more frequently by right-handed than left-handed surgeons (53.7% vs. 30%, $p=0.041$). Left-hand symptoms were not significant with left-handed surgeons. Women reported right-arm symptoms more commonly than men (66.7 vs. 50.8%, $p=0.03$), while men reported more lower-extremity symptoms (34.2 vs. 20.4%, $p=0.047$). Surprisingly, symptoms were little related to age, height, or practice length. Far beyond previous reports of 20-30% incidence of occupational injury, we presented evidence that 87% of surgeons who regularly perform MIS suffer such symptoms/injuries, primarily high-case load associated. As laparoscopic procedures become more prevalent, additional data accrual and analysis is necessary for improvement of surgeon-patient and surgeon-technology interfaces to reverse this trend and halt the epidemic before it is upon us.

- **Study 10: Joint kinetic data analysis using biomechanical modeling for ergonomic risk assessment of laparoscopic camera assistant [2-11]**

  Kinematic data analysis has been used consistently as an ergonomic assessment tool to describe the angular joint movements of primary laparoscopic surgeons.[13, 18-21] In the first leg of this study, we collected biomechanical data through force plates and quantified weight loading as distributed between two legs to investigate the ergonomic risk caused by the posture of the camera assistant during a simulated Nissen fundoplication. In this study we posited that kinetic data analysis to describe how internal and external forces interact together during joint movement is essential and must be coupled with kinematic data analysis. Seven laparoscopic

surgeons performed camera-navigation and tissue retraction tasks at a box trainer which was placed on an OR table to simulate an adult patient in low lithotomy position (Same experiment setup used in study 8). Joint compressive loading at the medial and lateral compartments of the joint will be calculated by a biomechanical model of the knee joint currently under development. The key concept of this model is mechanical equilibrium. The internal forces generated by ligaments (anterior and posterior cruciate and medial and lateral collateral ligaments) and muscles (quadriceps, hamstring, and gastrocnemius muscles) must balance the external forces (e.g. gravity) acting on the limb segments (Fig.1 and 2). The data inputs to this model included the joint forces and bending moments at the knee, flexion/extension angles at the hip and knee, and vertical ground-reaction forces from force plates. Using these inputs, our biomechanical knee model, written in Matlab programming language, calculates the load distribution at the medial and lateral compartments of the knee joint. Axial knee force which is the most influential element of compressive load at this joint significantly increased with proximal targets (700%BW) compared to distal targets (570%BW), a result of the distal position of the camera. Calculating and analyzing joint force data makes an important contribution to the kinetic data analysis necessary for surgical ergonomics. In this study we demonstrated that the joint force of the left leg in the compressive direction was 5.7 to 7 times that of each subject's body weight. Overall, the biomechanical analysis performed in this research showed that camera assistants are in a high-risk ergonomic situation. Additionally, our research confirmed the potential of using a more detailed biomechanical model – that incorporates joint kinetic data – for the provision of more practical, useful information that will result in feasible ergonomic solutions such as camera-handle attachments, instructions for weight rebalancing, or an assistant's stool as means for minimizing fatigue and maximizing postural stability.

Cognitive Ergonomics

Although the REVEAL project was initially designed to focus on physical ergonomics, we came to appreciate that cognitive ergonomics were also major issues in minimally invasive surgery. Specifically, the increased mental demand required to navigate using a small field of view and working within a framework that required mental rotations to stabilize the surgeon's perspective relative to the camera's, were significant challenges. Although new display techniques and tool designs might reduce some of these cognitive requirements, we felt that there were few established means of assessing such cognitive outcomes within the context of MIS.

At the time we began our cognitive ergonomics studies, there were relatively few studies that focused on the systematic assessment of cognitive issues (outside of those devoted to the design and assessment of surgical training), although there was ample anecdotal evidence that surgeons found MIS to be more "cognitively stressful" than open procedures. Our goal during the project was to initiate the selection, design, and use of potential cognitive state measures to be used in the assessment of laparoscopic tools and displays. To that end, we explored the use of two secondary task measures of mental workload, as well as one subjective measure of workload, one subjective measure of stress, and one secondary task (global implicit measure) of situation awareness.

Review of Candidate Workload Assessment Techniques

Our initial step was to review the current mental workload, situation awareness, and stress metrics used in other high-risk, safety-critical systems. We mainly focused on aviation

because of the similar high demand for precise perceptual-motor skills as well as similar issues related to navigation, wayfinding, and disorientation. The result of this review was published in *Surgical Innovations*[22]. Based on our review of workload techniques used in other domains, as well as our review of cognitive task analyses related to surgery, we recommended the use of one of each of the three main types of workload assessment techniques – physiological metrics, subjective metrics, and secondary task performance metrics. In the case of physiological metrics, we recommended that eye tracking be given consideration because such measures could provide a dual benefit. Not only could they potentially track changes in workload throughout the course of a procedure (e.g., blink duration and pupil diameter), but they could also track the surgeon's utilization of different screen elements, allowing better display configurations in future iterations of visualization support tools. With respect to subjective measures, we focused on the NASA-TLX because of its extensive history within aviation, and because of its successful application to other work domains. We also suggested that facet measures of workload might be important in surgery in order to allow us to diagnose particular issues contributing to instances of high workload. With respect to secondary task measures, we recommended that serious consideration be given to time estimation. This suggestion was made based on reports that surgeons use their "mental clocks" in making strategic decisions during surgeries. Research in aviation contexts has found greater time estimation variability during periods of peak workload when people are asked to produce the same interval over and over during a performance test. There have also been reports of overestimation of intervals as a function of increased task demand. We also considered the possibility of using visual detection as a secondary task to measure residual capacity not consumed by the primary surgical tasks.

A Visual Detection Secondary Task Measure of Surgical Workload

The goal of our initial laboratory experiment on mental workload metrics focused on the use of a visual detection secondary task and the use of the NASA-TLX. The secondary task involved the presentation to the peripheral visual field of red circular stimuli that increased in size at a constant pace until detected by the current research participant. Time to detection was the main dependent measure. As a primary task, participants performed either computerized target acquisition tasks or, alternatively, simple bead transfer tasks using an actual laparoscopy training stand. The circular stimuli were presented in an annulus around the central (primary task) display. We manipulated the difficulty of the primary task by varying either control-display lag (longer lags resulting in more difficult task scenarios) or we used target size (moving beads to a dish is easier than threading the same beads on a pegboard).

Unfortunately, we were unable to obtain consistent discriminations of the easy from difficult tasks using the detection secondary task measure. In part, this was due to a tendency for subjects to refocus their attention on the secondary task stimuli (red circles) rather than maintaining attention on what should have been the actual primary task (e.g., beads, dish, pegboard). Although the detection task was not sensitive to workload, the NASA-TLX showed a very high level of sensitivity. As a result, we retained the NASA-TLX as a workload measure, but we decided to abandon the visual detection task as a secondary performance task metric and turned instead to time estimation as a performance-oriented secondary task.

Interval Productions (Time Estimation) as a Measure of Mental Workload

After determining that a visual detection secondary task measure of workload was too obtrusive to yield sensitive distinctions between tasks requiring different perceptual-motor

demands, we decided to pursue a secondary task that is more truly embedded, naturally, in actual surgical performance – informal time keeping. That is, we looked for a task with greater content and face validity. In particular, using the same primary tasks described above, we asked participants to say "time" every time they felt that a set period (31 seconds in our first experiment on time estimation) had elapsed. Our primary measure was the ratio of the median true interval during a 2-minute trial to the target interval (31 sec.). Unlike the detection secondary task, the "cue" was internal, and therefore was less likely to disrupt primary task performance. Instead, deterioration in the secondary task should occur with increases in primary task demand. Lio et al. (2006)[23] found evidence that time estimation did work in the predicted fashion, although this measure did not appear to be as sensitive to workload differences as global NASA-TLX scores.

As a follow-on study, we manipulated the duration of the target interval that research participants produced in order to see if shorter (or longer) intervals resulted in more sensitive estimates of workload. In particular, we studied intervals from 6 to 41 seconds (in 5-sec increments). Our findings (in preparation) indicate that intervals as short as 6 seconds result in workload estimates that are as sensitive as our longer (31 sec) intervals. However, estimates in the 16-sec. range appear to be relatively insensitive. The lack of sensitivity of the 16-sec. interval productions could, hypothetically, reflect the transition point from subjects relying on working memory to relying on prospective and long-term memory, thus resulting in more variability among participants and reduced statistical power.

To summarize, time estimation appears to be an adequate index of mental workload, at least for simple laparoscopic training tasks; however, we must continue to explore the procedural factors that will further increase the metric's sensitivity (e.g., duration produced, method of instructing participants, method of summarizing performance data).

Measurement of Subjective Stress: The Short Stress State Questionnaire

In addition to measuring mental workload, we wanted to capture other dimensions of subjective state that might influence long-term performance. Mental stress was one such construct, divided as it commonly is within the psychological literature into cognitive (worry), affective (distress), and motivation (engagement) components. Clearly, the last of the three components of this multidimensional conceptualization of stress can be seen as positive with respect to potential performance, although the other two components are likely to be negative.

Once again using the transfer tasks described above (dish to bucket vs. dish to pegboard), research participants rated their stress levels using the Short Stress State Questionnaire (SSSQ), based on the Dundee Stress State Questionnaire (DSSQ). It should be noted that it is not automatically the case that stress follows the same pattern as workload in response to changing task demands. For example, increased workload may lead to greater OR less engagement, depending on personal coping strategies and ability level, among other factors. In our study, we found that performance enhancements due to practice were associated with decreased worry, while enhancements related to task design itself were associated with reductions of distress. In our tasks, when distress was high, performance effects might have been exacerbated because participants tended to disengage in these conditions.

In highlighting distinctions between the effects of training vs. task design interventions on stress, we felt that the SSSQ showed promise as an evaluation tool. It provided results that were not directly or simply correlated with task demand (see Carswell et al, MMVR 2007[24]).

We were later able to replicate the findings of our initial use of the SSSQ in a scenario looking specifically at the impact of visualization factors on stress[25]. Specifically, in a ring transfer task, we looked at the separate and joint effects of target resolution (manipulated by introduction of a "blood" smear across the laparoscopic field) and display rotation (rotation 90-degrees from the optimal collinear display-to-participant arrangement). Once again, practice yielded reductions in worry, while display manipulations resulted in changes in distress. We believe that these task combinations, along with the SSSQ, might be useful to present to surgical students to determine the stress coping mechanisms used by each, and to provide stress resistance training tailored to their stress response profiles.

A Global Implicit Measure of Situation Awareness

In addition to mental workload and stress, situation awareness has become a favored meta-measure for overall (and more importantly, projected) performance in complex tasks. The rationale behind the interest in measuring situation awareness is that an expert who is performing a task well will have a detailed and accurate internal situation model that allows her to detect the presence of critical environmental cues, to understand the importance of those cues for current actions, and to allow for the prediction of future states in order to plan for effective future actions. Although the concept certainly seems to capture important aspects of expert performance, it proves to be hard to measure. We wanted to see if we could come up with a measure that was applicable to relatively simple training tasks in order to determine whether students are using residual cognitive capacity, presumably freed up by practice, to maintain a global situation model and to plan ahead. Although most common situation awareness metrics involve task interruptions to probe the participant's understanding of the current and future status of task events (e.g., SAGAT), we opted to develop a global implicit measure (GIM). GIMs infer the presence of good situation models by detecting the participant's adoption of performance strategies that would be unlikely without such models. Lio et al. (2007)[26] asked participants to practice moving multi-colored rings from a dish to a pegboard across nine 2-minute trials. In the beginning, all the rings had the same size inner diameter. However, between the third and fourth trials, unknown to the research participants, the same-size rings were exchanged for a set of rings with variable interior diameters. The smallest diameters were more difficult to thread onto the pegs than were the rings with the largest interior diameters (the exterior diameters for all rings were matched). Furthermore, the "easiest" sizes were all one color and the "hardest" sizes were all a different color. If a person had good situation awareness, we reasoned, then he should quickly figure out that 1) some rings were more difficult to thread than others, and 2) that the difficult rings were all color X, and thus Color X rings should be avoided. Based on the pattern of color use, we could determine the degree to which environmental cues were being well used by our research participants. We argue that this relatively simple method could be used for evaluating the impact of display design, stress, and training on an important outcome measure thought to be a good predictor of accident and incident involvement.

Production of Research Media

Throughout this project we pursued a goal of media production and documentation for all aspects of the project. In order to promote the research results and methods we produced a half-hour piece for the Research Channel, which was delivered and reviewed for airing during spring 2007. We attended the Research Channel's annual meeting in Chicago, where we made a presentation detailing our methods and results from the media efforts within the REVEAL project.

Fig. 2: Screen shots from media produced to air on the Research Channel about the goals and accomplishments of the

In support of the documentation of REVEAL research, we shot video and interview footage at UMMC to record work being done there by Gyusung Lee in the Simulation Center related to physical ergonomic assessment. This provides documentation of process and goals, results, interviews with principal researchers, and descriptions of equipment setup and renovations necessary to support the research.

We also documented the work in cognitive ergonomics being conducted by Melody Carswell at the University of Kentucky. We documented the controlled experiments being done in the REVEAL laboratory, including interviews with students, who explain in detail the experimental design. We also experimented with stereo video acquisition for our research with stereo displays, including the capture of stereo still images taken with the REVEAL camera and a special lens.

We attended the "Operating Room of the Future" conference in Baltimore, MD, and recorded talks and interviews by all REVEAL team members, including Adrian Park, W. Brent Seales, Melody Carswell, Gyusung Lee, and Ivan George. We also interviewed invited speakers and TATRC personnel (Gerald Moses and Amy Nyswaner).

Supported Personnel

The following is a list of personnel receiving pay from the research effort.

Donald Bruce Witzke
Linda S Rice
William B Seales
Praveen Kumar Devabhaktuni
Stephen P Bailey
Ryan Davis
Kenneth Fouts
George Landon
Yun Lin
Josiah J Gustavison
Jonathan D Greenhoe
Matthew Douglas Field
Zachary Hawk Berkshire
Catherine M Carswell

Charles A. Martin
Robert Shapiro
David T Berry
Charles Pike
Kim Hall
Ivan George
Jesus Caban
Yogesh Shukla
Mary Bond
Michael Jacobs
Dan Lau
Huay Khoo
Scott McIntosh

Key Research Accomplishments (Summary)

- Stereo probe calibration
- Large-Scale Projection of Stereo Images from Laparoscopic Probe
- Deployment of the REVEAL Display System at UMMC Simulation Center

- Identifying compensatory and strategic joint movements and their effect on postural instability
- Performing the first systematic series of analysis of postural sway and stability demand during the performance of laparoscopic tasks
- Developing novel methodologies for force plate and posture data analysis
- Developing unique analysis methodology using sub-task analysis for identification of characteristic joint movement patterns used by expert laparoscopic surgeons
- Identifying optimal operating room table height for better ergonomics in posture and better surgical outcomes
- Undertaking the first assessment of ergonomic risk associated with assisting in laparoscopy
- Completing the most comprehensive literature review in surgical ergonomics to date
- Undertaking and completing the most comprehensive ergonomic survey study to date with results showing that among other issues about 90% of laparoscopic surgeons experience extreme fatigue and/or physical complications that are mostly related to case load with surgeon's age being discounted a as a causative factor
- Developing a biomechanical model of the knee joint to analytically calculate the distribution of knee joint compressive force

- Completing a review of the mental workload literature with recommendations about the application of such measures to surgical environments.
- Performing an experiment evaluating the use of a visual detection task as a possible secondary task workload metric. Results indicated that this particular technique was not well-suited for the surgical environment.
- Performing a series of experiments evaluating and demonstrating the potential utility of interval production as a secondary task measure of mental workload.
- Evaluating the use of a subjective stress measure, the Short Stress State Questionnaire (SSSQ), for the development of stress profiles for different training regimens and for tool modifications.
- Developing a global implicit measure of situation awareness that is applicable to even the earliest training stages of surgical performance assessment.
- Deploying a battery of time estimation, subjective workload, and stress measures to researchers at the University of Maryland for use in combination with their physical ergonomics techniques in assessing surgical tools and innovations.

Reportable Outcomes

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Lee G, Surgical Ergonomics in Minimally Invasive Surgery, Department of Physical Therapy, University of Maryland, MD, April 27, 2007
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2008 NOSCAR Olympus Medical Systems Research Award

Title: Quantitative ergonomic assessment of NOTES techniques: a study of physical and mental workload, body movement and posture
Adrian Park, Gyusung Lee, Carlos Godinez, F Jacob Seagull, Lee Swanstrom, Bin Zheng
Duration: 09/2008 – 08/2009
Amount: $86,750

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Conclusion

From its inception project REVEAL has focused on three major areas related to the practice of minimally invasive surgery—(1) technology enhancing existing tools and techniques or enabling the creation of new tools and techniques; (2) methods for evaluating the physical impact of the practice of minimally invasive surgical on surgeons; and (3) methods for evaluating the impact of changes in tools or techniques on the performance of surgeons. In each of these areas project REVEAL has made significant progress in defining and evaluating new approaches.

The technology being used in the practice of minimally invasive surgery at the outset of project REVEAL typically consisted of a camera, camera signal controller/conditioner, and CRT or LCD display. There was no opportunity to insert software control or enhancement of images in this stream. By the conclusion of project REVEAL we have shown that the image processing stream between camera and display can tolerate real-time image processing without adding sufficient image latency to impact the surgical experience. We have used this opportunity for image processing to create a display architecture supporting real-time processing and display of surgical images. We have created prototypes of functions that we expect to be useful to both researchers and clinicians, including large scale high pixel density displays of real-time surgical images, and dynamic overlays for the surgical image. Continued improvements in software and hardware performance will enable increasingly valuable and elaborate real-time and off-line image enhancements.

Project REVEAL's emphasis on measurement of physical challenges in the practice of minimally invasive surgery followed preliminary experiments at the University of Kentucky of Medical Center involving the use of force plates to measure changes in the way surgeons bore their weight during procedures. REVEAL has significantly elevated the sophistication and specificity of these types of evaluations by incorporating techniques commonly used in sports medicine or rehabilitative medicine to evaluate physical demands of performance in real-time. As reported, we have made significant contributions to the theory and practice of measurement and evaluation of physical ergonomics during the performance of minimally invasive surgical procedures.

The creation of new surgical tools, or the change of surgical procedure based on alternatives suggested by the evaluation of physical ergonomics, necessitates the evaluation of new practices relative to existing techniques. Though the gold standard for evaluation is always patient outcomes, the accumulation of enough data from enough patients to produce meaningful evaluative information is virtually impossible for the kinds of incremental improvements we are considering. To reduce the burden on researchers, project REVEAL has proposed and demonstrated new proxy measures that could be used in such scenarios. These much simpler, much less invasive, much more easily gathered proxy measures form the basis for quantitative comparison of alternatives where no meaningful quantitative evaluation was possible before.

Taken as a whole, we believe that results of project REVEAL demonstrate a significant contribution to the engineering and analysis of systems and clinician performance in the minimally invasive surgery domain. Work continues to enable more elaborate computer image processing and feedback based on the endoscope image screen, to evaluate critical movements

made by practitioners that can be changed or eliminated to reduce the physical burden on surgeons, and to provide a quantitative basis for the evaluation of small-scale changes to existing practices.

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